

REPORT DOCUMENTATION PAGE				Form Approved OMB No. 0704-0188	
<small>Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Washington Headquarters Service, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington, DC 20503.</small>					
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.					
1. REPORT DATE (DD-MM-YYYY)		2. REPORT DATE		3. DATES COVERED (From - To)	
18-11-2002				Dec. 98-Nov. 02	
4. TITLE AND SUBTITLE HF Radar Measurements of Ocean Surface Currents and Winds.				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				N00014-99-1-0174	
				5c. PROGRAM ELEMENT NUMBER	
				NONE	
6. AUTHOR(S) John F. Vasecky				5d. PROJECT NUMBER	
				99PR02698-00--	
				5e. TASK NUMBER	
				NONE	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Michigan Division of Research 3008 South State Street Ann Arbor MI 48109-1274				5f. WORK UNIT NUMBER	
				SPRL 224500	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research Ballston Centre Tower One 800 North Quincy Street Arlington VA 22217-5660				8. PERFORMING ORGANIZATION REPORT NUMBER	
				I00 873 EDI/EFT number 7129AC	
				10. SPONSOR/MONITOR'S ACRONYM(S)	
				ONR	
				11. SPONSORING/MONITORING AGENCY REPORT NUMBER	
				ONR 252	
12. DISTRIBUTION AVAILABILITY STATEMENT Unlimited					
13. SUPPLEMENTARY NOTES N/A					
14. ABSTRACT See Attached Report					
15. SUBJECT TERMS See Attached Report					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
					19b. TELEPHONE NUMBER (include area code)

20021127 026

HF Radar Measurements of Ocean Surface Currents and Winds

John F. Vesecky

Electrical Engineering Department, University of California at Santa Cruz
221 Baskin Engineering, 1156 High Street, Santa Cruz CA 95064
phone: (831) 459-4099 fax: (831) 459-4829 email: vesecky@cse.ucsc.edu

Atmospheric, Oceanic and Space Science Department, University of Michigan
2455 Hayward Road, Ann Arbor MI 48109-2143
phone: (734) 764-5151 fax: (734) 764-5137 email: jfv@engin.umich.edu

Award Numbers: N00014- (UCSC) and N00014--99-1-0174 (UM)

LONG-TERM GOAL

Our long term goal is to develop multifrequency, high frequency (HF) radar techniques and instrumentation for measuring surface currents, vertical shear, winds, friction velocity and waves in coastal regions and large lakes for scientific, civil and military applications. Our goal includes deployment of HF radar systems for air-sea interaction, coastal oceanography and ship detection research as well as the integration of HF radar measurements into coastal ocean models. A related goal is to investigate and develop ship detection and tracking techniques for multifrequency HF radar.

OBJECTIVES

The objectives of this project began with the construction and deployment of two and later three multifrequency HF radar instruments (called MCR for Multifrequency Coastal Radar) to Monterey Bay, California. Further experiment deployments were to the Virginia coast and to Lake Michigan for fresh water experiments (NSF sponsorship). The data collected at these sites is reduced, analyzed and interpreted to achieve the specific research objectives listed below:

1. Improvement of radar performance by upgrading hardware and software and developing improved transmit antennas, signal processing and flexible use of multiple frequencies
2. Improvement of HF radar estimates of surface currents, vertical shear, winds, friction velocity and waves by improved estimation algorithms that use knowledge of air-sea interaction physics
3. Estimate surface wind speed and direction using multifrequency HF radar measurements by exploiting air-sea interaction physics and HF radar measurements of vertical current shear
4. Ocean science investigations, including assimilation of HF radar data into coastal ocean models for circulation, chemical and biological properties as well as air-sea interaction studies
5. Use of continuing HF radar observations on Monterey Bay in observing ships to assess the usefulness of multiple frequency HF radar in ship detection and tracking.

APPROACH

This project requires an expert team of engineers and oceanographers from many institutions, including Peter Hansen and Lorelle Meadows (University of Michigan), Calvin Teague (Stanford University),

Dan Fernandez (California State University, Monterey Bay), Jeff Paduan (Naval Postgraduate School) and Kenneth Laws, Jessica Drake and Steve Petersen (University of California at Santa Cruz). This team designed, constructed, upgraded and deployed MCR's at sites on the Atlantic and Pacific oceans as well as the Great Lakes. We continually seek to deploy MCR systems for air-sea and ship observations in both short campaigns and long-term observations. A summary follows:

1. **Ocean science investigations:** participate in investigations of air-sea interaction, including momentum transfer and structure of the air and sea boundary layers and the assimilation of HF radar data into the coastal ocean circulation models
2. **Improve radar performance** by upgrading radar hardware and software, repairing and upgrading the radar antennas, especially transmit antennas; and comparing MCR with other HF systems
3. **Improve HF radar estimates of surface currents, current shear, winds and friction velocity** by developing improved estimation algorithms that use air-sea interaction physics, e.g. the Charnock relation, and continued work on MUSIC, rootMUSIC and beamforming
4. **Estimate surface wind vectors using multifrequency HF radar** measurements by using statistical techniques, air-sea interaction theory and the HF vertical current shear measurements
5. **Use the continuing HF radar observations on Monterey Bay to observe ships** (especially known ships at known locations) at multiple HF frequencies, noting changes in detection and tracking performance with frequency, range, direction, ship type, etc.

WORK COMPLETED

1. **Observational program:** We strive to keep the MCR units in operation either at Monterey Bay, their 'home site', or employed in experimental campaigns elsewhere. During the last year two MCR's operated on and near Monterey Bay. This includes monitoring, maintenance and upgrades.

2. **Estimation of wind friction velocity (u^*) using multifrequency HF radar:** Multifrequency HF radar observations of currents at different depths are used to find u^* -- see Meadows (2002).

3. **Evaluation of Root-MUSIC processing for HF radar:** We assessed the usefulness of this specialized form of MUSIC processing for linear HF radar antenna arrays -- see Teague (2002).

4. **Comparison of MCR and SeaSonde measurements of surface currents on Monterey Bay CA:** We compared surface current measurement results of MCR and SeaSonde (CODAR Ocean Systems instrument) systems using data from co-located sites -- see Vesecky et al. (2001 & 2002).

5. **Retrieval of vector winds using multifrequency HF radar measurements:** Partial least squares estimation to estimate vector winds; estimates were compared to buoy measurements.

6. **Communication of research results:** This year we presented eight papers at four major conferences and workshops on remote sensing and oceanography, including IGARSS and the Radio Oceanography Workshop, sponsored by ONR. One refereed journal paper was published.

7. **Ph. D. student graduated:** We are pleased that Lorelle Meadows received her Ph. D. degree in June 2002 from the University of Michigan (see Meadows, 2002 below).

RESULTS

This year produced many new results with the analysis of past field observations as well as collection of new data. Below are two examples that are particularly important to the field. One concerns the retrieval of friction velocity from multifrequency HF radar observations and comparison with buoy measurements and the other concerns the prediction of vector winds using HF radar data.

During the MUSE experiment of autumn, 2000 multifrequency coastal radars (MCR's) at Moss Landing and Santa Cruz on California's Monterey Bay made HF measurements that covered the location of the NPS flux buoy near the Moss Landing radar site. This buoy was capable of measuring friction velocity in the air as well as other air-sea interaction parameters. As her Ph. D. thesis project, Lorelle Meadows used data from these radars as well as the flux buoy to develop and test a technique for retrieving friction velocity from MCR measurements. The approach to the friction velocity measurement begins by assuming that the vertical current profile follows the logarithmic (law of the wall) theory for a turbulent boundary. Although there is some controversy regarding a linear variation close to the surface and experiments to support both the linear and the logarithmic views, the difference is not critical to this method. The fundamental direct measurement of the HF radar is the Doppler shift and hence the phase velocity of the radially traveling Bragg resonant waves on the ocean surface, i.e. ocean waves at wavelengths of $\approx 6.9, 11.2, 22.1$ and 31.3 m. The Bragg resonant waves traveling radially with respect to the radar, are half the radar wavelength and give rise to the HF radar echoes. The phase velocity (c_p) of surface waves affected by near surface currents can be estimated to first order by a weighted integral over depth z of the vertical current profile $U(z)$, $c_p = (g/k)^{0.5} + dc$ where $dc = 2k \int U(z) e^{2kz} dz$, where k is the wavenumber of the Bragg resonant ocean wave and $g = 9.8 \text{ m/s}^2$. The law of the wall says that $U(z)$ depends on friction velocity in the water u_{*w} and roughness length, z_0 .

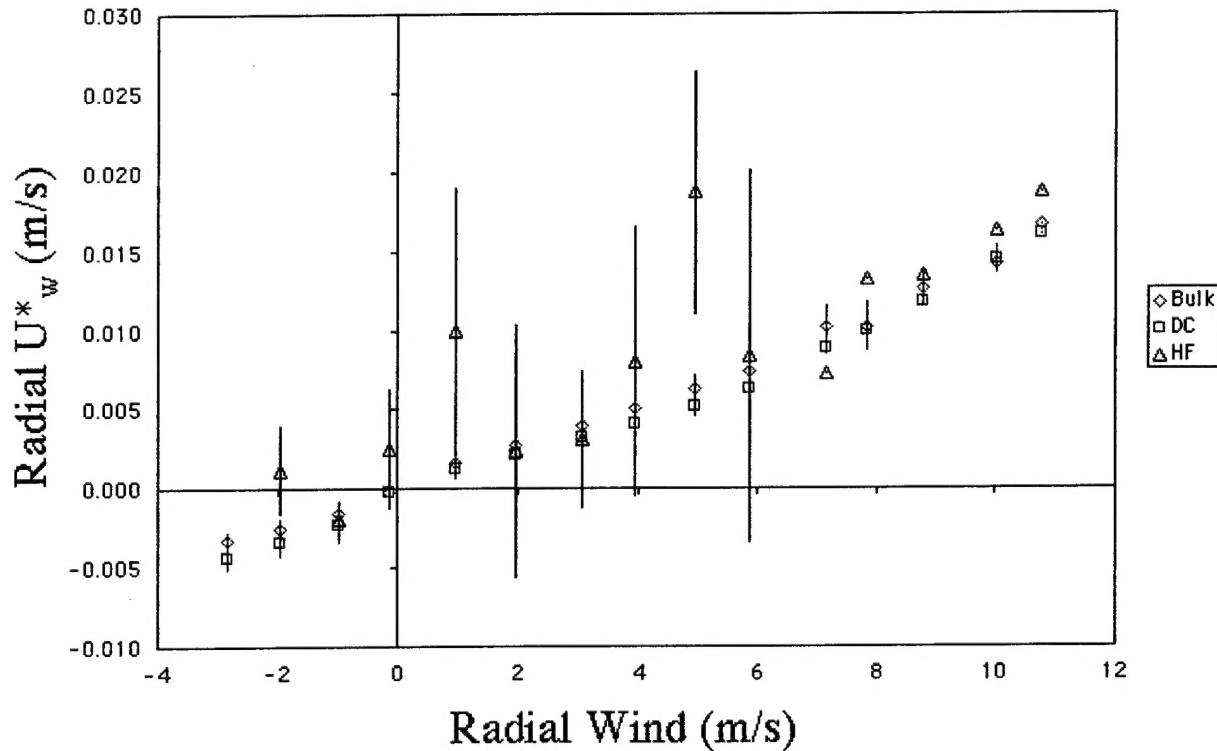


Fig. 1. Comparison of estimates of u_{*a} . The colored square and diamond are estimates from the NPS flux buoy using a bulk parameter estimation, using air-sea measurements, and a direct calculation (DC), found by direct correlation of wind field fluctuations. The multifrequency coastal radar (MCR) estimates are made as described in the text. Radial refers to along the HF radar line of sight, i.e. all the u^* estimates are projected onto this line of sight.

The Levenberg-Marquart nonlinear estimation technique is used to find values of u_{*w} and z_0 which minimize the differences between the observed and predicted values of c_p . Once u_{*w} is estimated, u_{*a} in the air can be found knowing that u^* scales with density, $u_{*w} = (r_a / r_w)^{0.5} u_{*a}$. Thus, HF estimates and

buoy estimates of friction velocity can be compared. Note that this method does not rely on an effective depth estimate for HF radar currents, but uses the Doppler observations directly.

For wind speeds above ≈ 6 m/s the HF radar estimates agree very well with the buoy measurements. At lower wind speeds one expects poorer results from the MCR because other factors, such as tides and buoyancy flows, are affecting the near surface currents and are presently ignored in the analysis. At any wind speed this method produces values of χ^2 , which tells one how well the model fits the measurements, and hence allows one to put error bars on the measurements. Note that aside from one case the buoy measurements are within the error bars of the MCR estimates. We regard these results as very promising for the use of multifrequency coastal radar in mapping friction velocity.

Multifrequency HF radar measurements reveal the vertical current shear near the ocean surface. Thus, we anticipate that wind speed and direction can be estimated from MCR data since wind stress on surface is usually the dominant factor in determining current magnitude and the vertical shear. Previous research has been successful in making wind direction estimates, but no really successful estimates of wind speed. In this study we did not try to employ a physical model as above, but for this initial effort choose a linear, empirical prediction method known as partial least squares. This method seeks a wind component estimate based on a weighted sum of all the input data components. The weights are determined by a least squares procedure. For the input data we used the surface currents at all depths as well as the wind direction estimated by the relative strengths of the first order Bragg peaks in echo

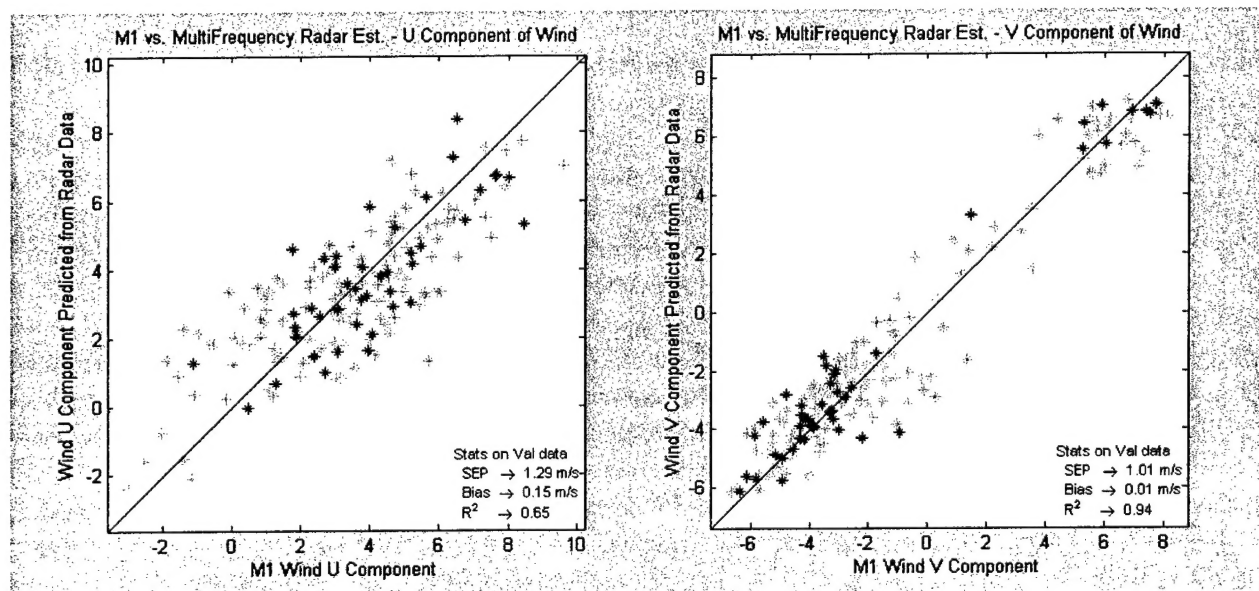


Fig. 2. Comparison of wind speed estimates from MCR with buoy winds. The standard error of prediction SEP is ≈ 1 m/s and bias ≈ 10 cm/s. Left (right) panel shows eastward (westward) U (V) component of the wind. Colored points are MCR estimates, whereas the gray points are the training set used to develop the partial least squares estimation algorithm.

Doppler spectrum. Weights derived by the partial least squares algorithm emphasized the following:

1. Input data from the highest radar frequencies, sensing nearest the surface, were most important.
2. Differences between currents estimated from radar data at two different frequencies were important – this reflects the importance of shear in the wind estimates.
3. Direction estimates from Bragg line ratios were important – this ratio estimates the wind

direction as established by a number of investigators in earlier work.

The results are impressive with the standard error of measurement, i.e. the standard deviation of the difference between HF and buoy measurements, being very near 1 m/s after removal of a very small bias, ≈ 10 cm/s. This level of estimation accuracy is sought by meteorologists, but seldom attained in remote sensing measurements. Further, the method does not appear to degrade at low wind speeds.

IMPACT/APPLICATION

Multifrequency HF radars have demonstrated their usefulness in measuring surface currents and current shear in the top few meters of the ocean. No other technique makes such measurements over a large area, at such low cost. We extended HF radar applications to fresh water and to mapping of friction velocity and wind vector. HF radar measurements are useful for real time applications.

RELATED PROJECTS

1. We participated in the Integrated Coastal Ocean Network (ICON) project (National Ocean Partnership Program), integrating in situ and remote measurements over Monterey Bay.
2. We began participation in the Center for Integrated Marine Technology that brings together physical, chemical and biological oceanographers as well as marine biologists to make and interpret measurements relevant to the Monterey Bay Marine Sanctuary (NOAA)

PUBLICATIONS

Lettvin, E. E. & J. F. Vesecky, Estimation of wind friction velocity and direction at the ocean surface from physical models & space-borne radar scatterometer measurements, **J. Geophys. Res. Oceans**, **106**, C10, 22,503-22,519 (2001).

Meadows, L. A., "High frequency radar measurements of friction velocity in the marine boundary layer," **Ph. D. thesis**, The University of Michigan (2002).

Teague, C. C., Root-MUSIC Direction Finding Applied to Multifrequency Coastal Radar, **Proc. IGARSS 2002**, IEEE Press, Piscataway NJ (2002)

Vesecky, J. F., J. Drake, C. C. Teague, D. Fernandez, C. Whelan, M. Plume, J. Paduan, P. Hansen, "Comparison of Surface Current Measurements by Different HF Radar Systems With Each Other and With ADCP Current Measurements," **AGU Ocean Sciences Poster**, Honolulu HI, Feb. (2002)

Vesecky, J. F., "Multiple-Frequency HF Radar Observations of the top few Meters of the Ocean: Air-sea Interaction & Circulation," **Werner Alpers Symposium: Achievements & Perspectives of Remote Sensing of the Ocean**, Hamburg, Germany, Sept. (2001) – invited paper

Vesecky, J. F., J. Drake, M. Plume, C. C. Teague, L. Meadows, Y. Fernandez, P. Hansen, K. Davidson & J. Paduan "Multifrequency HF Radar Observations of Surface Currents: Measurements from Different Systems and Environments," **Proc. OCEANS 2001 MTS/IEEE Conference**, IEEE Press, Piscataway NJ (2001)

Vesecky, J., J. Drake, C. Teague, F. Ludwig, J. Paduan & K. Davidson, Measurement of wind speed & direction using MCR radar, **Proc. IGARSS 2002**, IEEE Press, Piscataway NJ (2002)

Papers presented at the **ONR Radio Oceanography Workshop**, April 2002 at Landeda, France

Teague, C. C., Root-MUSIC processing of multifrequency coast radar data

Vesecky, J. F., MCR and SeaSonde Comparison

Vesecky, J. F., Vector winds from multifrequency HF radar